The X-ray afterglow flat segment in short GRB 051221A: Energy injection from a millisecond magnetar?

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ABSTRACT

The flat segment lasting $\sim 10^4$ seconds in the X-ray afterglow of GRB051221A represents the first clear case of strong energy injection in the external shock of a short GRB afterglow. In this work, we show that a millisecond pulsar with dipole magnetic field $\sim 10^{14}$ Gauss could well account for that energy injection. The good quality X-ray flat segment thus suggests that the central engine of this short burst may be a millisecond magnetar.

Key words: Gamma Rays: bursts−GRBs: individual (GRB 051221A)−ISM: jets and outflows–radiation mechanisms: nonthermal

1 INTRODUCTION

GRB 051221A was localized by the Burst Alert Telescope (BAT) onboard the *Swift* satellite (Parsons et al. 2005) and promptly observed by both *Swift*/BAT and the Konus-Wind instrument. The Swift observations reveal this is a short hard burst, with $T_{90} = 1.4 \pm 0.2$ s, a hard photon index $\alpha = -1.39 \pm 0.06$, and a fleunce $1.16 \pm 0.04 \times 10^{-6}$ ergs cm^{-2} in the 15-150 KeV band (Cummings et al. 2005). The Konus-Wind cutoff power-law spectral fitting, in the 20-2000 KeV band, shows a fluence $3.2^{+0.1}_{-1.7} \times 10^{-6}$ erg cm^{-2}, a low-energy photon index $\alpha = -1.08 \pm 0.14$, and an observed peak energy $E_{\text{peak}} = 402^{+93}_{-72}$ KeV (Golenetskii et al. 2005). With a redshift $z = 0.5459$ (Soderberg et al. 2006), this burst's isotropic prompt emission energy is $E_\gamma \sim 2.4 \times 10^{51}$ erg, using the ΛCDM concordance model of $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $h = 0.71$.

Both the X-ray ($\sim 10^2 - 2 \times 10^6$ s) and the optical ($\sim 10^4 - 4 \times 10^5$ s) afterglow light curves of GRB051221A have been well detected, while in the radio band only one data point followed by several upper limits is available. This burst is distinguished by an X-ray flattening at $t \sim 0.03 - 0.2$ day, which strongly suggests a significant energy injection (Soderberg et al. 2006; Burrows et al. 2006). However, the nature of that energy injection is not clear. In the widely accepted double neutron star merger model for the short/hard burst, supported by the lack of detection of the bright supernova component in the current event (Soderberg et al. 2006),

the material ejected in the merger is $\sim (10^{-4} - 10^{-2}) M_\odot$ (Rosswog et al. 1999; Ruffert & Janka 2001). Given an energy conversion efficiency ~ 0.001, the fall-back accretion of part of that material onto the central post-merger object is not likely to be able to pump energy up to $\sim 10^{52}$ erg, even with moderate beaming correction. So the fall-back accretion model, which may give rise to significant energy injection in the collapsar scenario of long/soft GRBs (MacFadyen, Woosley & Heger 2001), does not work in the current case.

In this Letter, we'll show that the afterglow undergoing an energy injection from a millisecond pulsar with a dipole magnetic field $\sim 10^{14}$ Gauss (i.e., a magnetar) well accounts for the multi-wavelength data. The good quality X-ray flat segment thus suggests that the central engine of this short burst may be a millisecond magnetar.

2 ANALYTICAL INVESTIGATION

In the long/soft GRB scenario, the energy injection caused by a millisecond pulsar has been discussed in some detail (Dai & Lu 1998; Wang & Dai 2001; Zhang & Mészáros 2001; Dai 2004; Ramirez-Ruiz 2004; Zhang et al. 2006). Similarly, provided that the gravitational wave radiation is not important, the dipole radiation luminosity of a magnetar can be estimated by

$$L_{\text{dip}}(t_b) \simeq 2.6 \times 10^{48} \text{ erg s}^{-1} \ B_{\perp,14}^2 R_{s,6}^6 \Omega_4^4 (1 + t_b/T_o)^{-2}, (1)$$

where $B_\perp$ is the dipole magnetic field strength of the magnetar, R_s is the radius of the magnetar, Ω is the initial angular

frequency of radiation, the subscript "b" represents the time measured in the burst frame, $T_o = 1.6 \times 10^4 B_{\perp,14}^{-2} \Omega_4^{-2} I_{45} R_{s,6}^{-6}$ s is the initial spin-down timescale of the magnetar, $I \sim 10^{45}$ g cm^2 is the typical moment of inertia of the magnetar (Pacini 1967; Gunn & Ostriker 1969). Here and throughout this text, the convention $Q_x = Q/10^x$ has been adopted in cgs units.

The energy emitted at t_b will be injected into the previous GRB ejecta at time T_b satisfying

$$\int_{t_b}^{T_b} [1 - \beta(\tau_b)]c d\tau_b = c\int_0^{t_b} \beta(\tau_b)d\tau_b \approx ct_b, \quad (2)$$

where β, in units of the speed of light c, is the velocity of the ejecta moving toward us. The corresponding observer time is

$$t \approx (1+z)\int_0^{T_b}[1 - \beta(\tau_b)]d\tau_b. \quad (3)$$

Equations (2) and (3) yield $t \approx (1+z)t_b + (1+z)\int_0^{t_b}[1 - \beta(\tau_b)]d\tau_b \approx (1+z)t_b$.

At time T_b, the energy injected into the ejecta satisfies $dE/dT_b = [1 - \beta(T_b)]L_{\text{dip}}(t_b)$. With the relation $dt = (1+z)[1 - \beta(T_b)]dT_b$, we have

$$\frac{dE}{dt} \approx \frac{1}{1+z}L_{\text{dip}}\left(\frac{t}{1+z}\right)$$
$$= \frac{2.6 \times 10^{48}}{(1+z)} \text{ erg s}^{-1} \ B_{\perp,14}^2 R_{s,6}^6 \Omega_4^4[1 + \frac{t}{(1+z)T_o}]^{-2} \quad (4)$$

So the energy injection rate $dE/dt \sim$ const for $t \ll (1+z)T_o$ and $dE/dt \propto t^{-2}$ for $t \gg (1+z)T_o$.

A general energy injection form can be written as $dE/dt = A(1+z)^{-1}(t/t_o)^{-q}$ for $t_i < t < t_f$, where t_i and t_f are the times when the energy injection takes place and turns off, respectively (Zhang & Mészáros 2001; Zhang et al. 2006). GRB ejecta's dynamical evolution, at a time t_c, is significantly changed when the injected energy roughly equals to its initial kinetic energy, i.e., $\int_{t_i}^{t_c}(dE/dt)dt \sim E_k$. We thus derive $At_o^q(t_c^{1-q} - t_i^{1-q}) \sim (1+z)(1-q)E_k$. Accordingly, our magnetar model requires $t_o = 1$, $t_i \sim 0$ and $q \sim 0$ for $t_c < (1+z)T_o$, which leads to $A \sim (1+z)E_\gamma/t_c$, and so

$$2.6 \times 10^{48} \text{ erg s}^{-1} \ B_{\perp,14}^2 R_{s,6}^6 \Omega_4^4 \sim (1+z)E_k/t_c. \quad (5)$$

For $t > (1+z)T_o$, the rate of the energy injection drops sharply or even the central supermassive magnetar has collapsed when it has lost significant part of the angular momentum, which indicates that the afterglow lightcurve flattening weakens at the time $t_f \geq (1+z)T_o$. So we have

$$1.6 \times 10^4(1+z)B_{\perp,14}^{-2}\Omega_4^{-2}I_{45}R_{s,6}^{-6} \sim t_f. \quad (6)$$

¿From equations (5) and (6), the total injected energy could be estimated as $E_{\text{inj}} = t_f E_k/t_c \sim 5 \times 10^{52}$ erg $I_{45}\Omega_4^2$. On the other hand, with and without energy injection, the contrast of forward shock X-ray emission flux can be estimated by (Kumar & Piran 2000)

$$f \sim (E_{\text{inj}}/E_k)^{(p+2)/4} \sim [5 \times 10^{52} \text{ erg } I_{45}\Omega_4^2/E_k]^{(p+2)/4}, \quad (7)$$

where $p \sim 2.4$ is the power-law index of the shocked electrons. Equations (5)−(7) are our main relations to constrain the physical parameters of the underlying magnetar.

From the X-ray observations of GRB051221A, we measure $t_c \sim 3000$ s, $t_f \sim 1.5 \times 10^4$ s, and $f \sim 6$. Sub-

stitute p and f into equation (7), we find $E_k \sim 7.6 \times 10^{51}I_{45}\Omega_4^2$ erg is well consistent with the observational result $E_k \sim 2E_\gamma \sim 4.8 \times 10^{51}$ erg when taking typical $I_{45} \sim 1.5$, $\Omega_4 \sim 0.65$ (i.e. 1 millisecond period), and the GRB efficiency $\eta = E_k/(E_k + E_\gamma) \sim 30\%$. Furthermore, the measurements of t_c, t_f, f, and p are well consistent with the constraint relation $f \simeq (t_f/t_c)^{(p+2)/4}$. *So we conclude that the central engine may be a magnetar.* Its physical parameters are $(\Omega, R_s, B_\perp, I) \sim (6500 \text{ s}^{-1}, 13 \text{ km}, 10^{14} \text{ Gauss}, 1.5 \times 10^{45} \text{ g cm}^2)$ according to the above constraint relations.

An additional constraint is on the ellipticity ϵ of the magnetar. As shown in Shapiro & Teukolsky (1983), the spin-down timescale due to the gravitational wave radiation is $\tau_{\text{gw}} \sim 3 \times 10^{-3}\epsilon^{-2}I_{45}^{-1}\Omega_4^{-4}$ s. Now $\tau_{\text{gw}} > t_f \sim 1.5 \times 10^4$ s, we have $\epsilon < 5 \times 10^{-4}I_{45}^{-1/2}\Omega_4^{-2}$.

3 NUMERICAL FIT TO THE AFTERGLOWS OF GRB 051221A

We interpret the apparent flattening in the X-ray light curve being caused by an energy injection from the central magnetar. Yet the flattening episode is unapparent in the optical and radio bands because of limited observations. The code here to fit the multi-band lightcurves has been used in Fan & Piran (2006) and Zhang et al. (2006), and has been confirmed by J. Dyks independently (Dyks, Zhang & Fan 2006). The dynamical evolution of the outflow is calculated using the formulae in Huang et al. (2000), which are able to describe the dynamical evolution of the outflow for both the relativistic and the non-relativistic phases. One modification is that now we have taken into account the energy injection (for instance see equation (12) of Fan & Piran (2006); see also Wei, Yan & Fan 2006). The electron energy distribution is calculated by solving the continuity equation with the power-law source function $Q = K\gamma_e^{-p}$, normalized by a local injection rate (Moderski, Sikora & Bulik 2000). The cooling of the electrons due to both synchrotron and inverse Compton has been considered. The synchrotron radiation of the forward shock electrons on the "equal arriving surface" (on which the emission reaches us at the same time) has been calculated strictly. The synchrotron self-absorption has also been taken into account strictly.

We consider a uniform relativistic jet undergoing the energy injection from the central source and sweeping up its surrounding uniform medium. The energy injection has been taken as $dE/dt = 2 \times 10^{48}$ erg s$^{-1}(1+t/1.5\times10^4)^{-2}$ for $t < 1.5 \times 10^4$ s otherwise $dE/dt = 0$ (i.e., we assume that the supermassive magnetar collapses when it has lost significant part of its angular momentum). As usual, the fractions of shock energy given to the electrons and the magnetic field (i.e., ϵ_e and ϵ_B) are assumed to be constant. Shown in Figure 1 is our numerical fit in the X-ray and optical bands with the following jet parameters: $E_k = 10^{52}$ erg, $\epsilon_e = 0.3$, $\epsilon_B = 0.0002$, the circumburst density $n = 0.01$ cm^{-3}, the half-opening angle $\theta_j = 0.1$, and the viewing angle $\theta_{\text{obs}}=0$ (i.e. on-beam viewing).

In addition, we find that a reverse shock emission component, besides the forward shock emission, should be evoked to account for the radio data, which is consistent with the finding in Soderberg et al. (2006). In the pulsar/magnetar energy injection scenario, the reverse shock
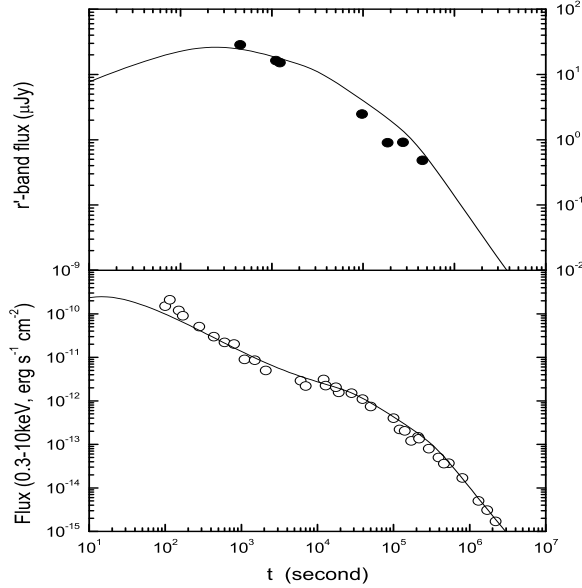
Figure 1. Modeling the XRT and R-band afterglow light curves of GRB 051221A with energy injection from an underlying millisecond magnetar. The optical and X-ray data are taken from Soderberg et al. (2006) and Burrows et al. (2006), respectively. The $r'-$band extinction of our Galaxy ~ 0.19 mag and that of the host galaxy ~ 0.2 mag (Verkhodanov et al. 2000) have been taken into account. The solid lines are our numerical results. Fitted parameters of the GRB jet undergoing energy injection are presented in Section 3.

emission has been calculated in Dai (2004), assuming that the outflow is electron/positron pairs dominated and the reverse shock parameters are similar to, or even larger than that of the forward shock. The resulting reverse shock emission is so bright that long-time flat bump should be evident in multi-band afterglow lightcurves. This prediction is not confirmed by current observations. This puzzle, however, could be resolved if the fraction of the reverse shock energy given to the electrons is very small, as shown below.

In our numerical code, the reverse shock dynamics/emission has not been taken into account. It is investigated analytically instead. We assume that the reverse shock emission accounting for the radio data is powered by the energy injection. Following Sari & Piran (1999), after the reverse shock crosses the ejecta at $t_\times$ (noted that at $t \sim t_\times \sim 0.2$ day the central magnetar collapses), the observed reverse shock emission flux $F_{\nu_\oplus} \propto (t/t_\times)^{-2}$ for $\nu_m < \nu_\oplus < \nu_c$, where ν_m is the typical synchrotron emission frequency of the shocked electrons and ν_c is the cooling frequency. On the other hand, $F_{\nu_\oplus} \propto (t/t_\times)^{-1/2}$ for $\nu_\oplus < \nu_m < \nu_c$. The current radio observation thus requires a $\nu_m(t_\times) \leq 8.46$ GHz. At $t_\times \sim 0.2$ day, the ejecta is at a radius $R \sim 7 \times 10^{17}$ cm and moves with a bulk Lorentz factor $\Gamma(t_\times) \sim 20$ (obtained in our numerical calculation), thus the comoving toroidal magnetic field of the magnetar wind is $B_w \sim [2L_{\rm dip}/(R^2\Gamma_w^2 c)]^{1/2} \sim 20/\Gamma_w$ Gauss, where Γ_w is the bulk Lorentz factor of the magnetar wind. In the reverse shock phase, the toroidal magnetic field will be amplified by a factor $\sim \Gamma_{\rm rsh} \approx \Gamma_w/2\Gamma(t_\times)$ for $\Gamma_w \gg \Gamma(t_\times)$ (Kennel & Coronitti 1984). On the other hand, the constraint $\nu_m(t_\times) \approx 2.8 \times 10^6 {\rm Hz} \, \gamma_{m(t_\times)}^2 \Gamma(t_\times)\Gamma_{\rm rsh}B_w/(1+z) \leq 8.46$GHz yields

$\gamma_{m(t_\times)} \leq 20$, where $\gamma_{m(t_\times)}$ is the minim random Lorentz factor of the electrons accelerated in the reverse shock front. Such a small[1] $\gamma_{m(t_\times)} \equiv 3\epsilon_e(p-2)(\Gamma_{\rm rsh}-1)m_p/[4(p-1)m_e]$ requires that the fraction of shock energy given to the electrons ϵ_e is in order of m_e/m_p because it is very likely that now $\Gamma_w \gg \Gamma(t_\times)$, where m_e and m_p are the rest mass of the electron and the proton, repsectively. Taking $\epsilon_e \sim m_e/m_p$ and $p \sim 2.3$, we thus have $\Gamma_{\rm rsh} \leq 115$ and $\Gamma_w \simeq 2\Gamma_{\rm rsh}\Gamma(t_\times) \leq 4600$. After the reverse shock phase, the magnetic energy may be translated to the forward shock mainly by the magnetic pressure working on the initial GRB ejecta and the shocked medium. However, the details are far from clear.

At $t \sim 0.91$ day, the 8.46 GHz emission flux is 0.155 mJy. Therefore the optical $(4.6 \times 10^{14}$ Hz) flux at $t_\times \sim 0.2$ day is ≤ 0.155mJy$(0.91/0.2)^2(4.6 \times 10^{14}Hz/8.46GHz)^{-0.65} = 2.7$ μJy. It is about one order lower than the forward shock optical emission. As for the X-ray, now $\nu_c(t_\times) \approx 2 \times 10^{15}$ Hz, the X-ray (at 2 keV) flux at $t_\times \sim 0.2$ day is ≤ 0.155mJy$(0.91/0.2)^2(2 \times 10^{15}Hz/8.46GHz)^{-0.65}(4.84 \times 10^{17}/2 \times 10^{15})^{-1.15} \sim 10^{-6}$ mJy, is also significantly lower than the forward shock X-ray emission. Our estimates made here are independent of the poorly known magnetized reverse shock dynamics. We thus conclude that the reverse shock X-ray/optical emission is unimportant and can be ignored.

One caveat is that the dipole radiation of the magnetar is almost isotropic. The medium surrounding the magnetar but out of the GRB ejecta cone would be accelerated by the energetic wind. Because the energy injected into the GRB ejecta is larger than that contained in the initial ejecta, the outflow contributing to the afterglow emission would be close to be an isotropic fireball rather than a highly jetted ejecta. So the magnetar energy injection model is somewhat challenged by the late jet break detected in GRB 051221A. However, this puzzle could be resolved if in other directions a large amount of baryons (~ 0.01 $M_\odot$) ejected in the double neutron star merger have existed there, as found in the previous numerical simulations (Rosswog et al. 1999; Ruffert & Janka 2001). The ejected material would be accelerated by the magnetar wind to a bulk Lorentz factor $\sim$ a few, provided that $E_{\rm inj} \sim 10^{52}$ erg. This wide but only mild-relativistic outflow will give rise to a very late ($\sim 10^6 - 10^7$ s after the burst) multi-wavelength re-brightening. However, for typical parameters taken in this Letter (the isotropic energy is 1.5×10^{52} erg and the initial Lorentz factor is 5.0, i.e., assuming the material ejected from the merger is about 1.5×10^{-3} $M_\odot$), the flux is not bright enough to be detectable. The emission peaks at $t \sim 3 \times 10^6$ s. The 0.3-10 keV flux is $\sim 1 \times 10^{-15}$ erg s^{-1} cm^{-2} which is marginal for the detection of *Chandra*, and the 8.46 GHz flux is ~ 0.01 mJy. Both are consistent with the extrapolation of current observations (Soderberg et al. 2006; Burrows et al. 2006). If an event like GRB 051221A takes place much closer, for

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[1] The numerical coefficient 3/4 is adopted because in the ideal MHD shock jump condition, the random Lorentz factor of the post-shock protons is proportional to $3(\Gamma_{\rm rsh}-1)/4$ rather than $\Gamma_{\rm rsh}-1$ (see eq. (17) of Fan, Wei & Zhang 2004b; see also Fan, Wei & Wang 2004a and Zhang & Kobayashi 2005 for numerical verification).

example, at $z \sim 0.1$, such very late multi-wavelength re-brightening may be detectable for *Swift* XRT or *Chandra* and other radio telescopes. This predication could be tested in the coming months or years.

4   DISCUSSION AND SUMMARY

Short hard GRBs may be powered by the merger of double neutron stars (e.g. Eichler et al. 1989). For GRB 051221A, ruling out of bright supernova component in the late optical afterglow lightcurve suggests that the progenitor probably is not a massive star and instead is consistent with the double neutron star merger model. After the energetic merger, a black hole (Eichler et al. 1989), or a differentially rotating neutron star (Kluźniak & Ruderman 1998; Dai et al. 2006), or a magnetar may be formed. Among the above cases the last one is based on various dynamo mechanisms (Rossowog, Ramirez-ruiz & Davis 2003; Gao & Fan 2006 and references therein) and in particular the MHD simulation of the two neutron star coalescence (Price & Rosswog 2006). How long can the supermassive magnetar survive? In the general-relativistic numerical simulation, the resulting hypermassive magnetar collapses in a very short time ~ 100 ms (Shibata et al. 2006). The hypermassive magnetar has a mass exceeding the mass limit for uniform rotating but the supermassive magnetar does not. Therefore a supermassive magnetar may be able to survive in a long time as shown in Duez et al. (2006). In view of the uncertainties involved in the numerical simulation, some constraints from the observation rather than just from the theoretical calculation are needed.

Thanks to the successful running of *Swift* and *Chandra*, now short GRBs could be localized rapidly and their X-ray afterglows could be monitored continuously. The X-ray flat segment in GRB 051221A strongly suggests a significant energy injection. Such an energy injection could be well accounted for if the central engine is a millisecond pulsar with a dipole magnetic field $\sim 10^{14}$ Gauss. The X-ray flat segment in GRB 051221A thus provides us a possible evidence for a long time living magnetar formed in the double neutron star merger. In this scenario, the material ejected from the merger would be swept and accelerated by the strong magnetar wind. This wide but mild-relativistic component would give rise to a very late multi-wavelength re-brightening and might be detectable for an event like GRB 051221A but much closer.

We would like to point out that the magnetar energy injection model is not unique to account for the data. For example, assuming the energy carried by the material of the initial GRB ejecta satisfies the relation $E(> \Gamma) \propto \Gamma^{-4.5}$ (Rees & Mészáros 1998; Sari & Mészáros 2000), the X-ray afterglow lightcurve of GRB 051221A could also be well reproduced (Soderberg et al. 2006; Burrows et al. 2006). However, the physical process pumping such kind of energy injection, in particular in the short GRB scenario, is not clear yet.

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